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DYNAMIC BLADE LOADING IN THE ERDA/NASA 100 kW AND 200 kW WIND TURBINES

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16. Abstract

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Dynamic blade loads, including aerodynamic, gravitational, and inertial effects, are presented for two large horizontal-axis wind turbines: the ERDA-NASA 100 kW Mod-0 and 200 kW Mod-0A wind power systems. Calculated and measured loads are compared for the experimental Mod-0 machine in operation at NASA's Plum Brook Station near Sandusky, Ohio. Predicted blade loads are also given for the higher power Mod-0A wind turbine now being assembled for operation as part of the municipal power plant of Clayton, New Mexico. Two major structural modifications have been made to the Mod-0 wind turbine for the purpose of reducing blade loads. A stairway within the truss tower was removed to reduce the impulsive aerodynamic loading caused by the tower wake on the downwind rotor blades. Also, the torsional stiffness of the yaw drive mechanism connecting the turbine nacelle to the tower was doubled to reduce rotor-tower interaction loads. Measured reductions in load obtained by means of these two modifications equaled or exceeded predictions.

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INTRODUCTION

National concern over the future availability of conventional fossil fuels has resulted in the initiation of many federal programs to investigate alternative sources of energy. One of these is the Federal Wind Energy Program, directed by the Energy Research and Development Administration (ERDA). Under the overall program management by ERDA, the Lewis Research Center of the National Aeronautics and Space Administration (NASA-LeRC) is responsible for developing large, horizontal-axis wind turbine generators. Current projects at LeRC include turbines with rotor diameters from 125 feet to 300 feet and generating capacities ranging from 125 kW to 2000 kW. Supporting research and technology is also being carried out to increase the reliability and reduce the cost of major components such as blades, drive train elements, and towers.

The blades of large wind turbines are continually collecting, amplifying, and transmitting dynamic loads. These loads may be aerodynamic, gravitational, or inertial in origin. Whatever their source, dynamic blade loads influence the weight and cost of almost all structural components in a wind turbine. Therefore, it is important that we continually develop and improve methods to predict and control dynamic loads in wind power systems.

The purpose of this paper is to document a measure of progress which has been made in understanding dynamic loads in large, two-bladed, horizontal-axis wind turbines. This will be done by presenting the solution to a serious dynamic loading problem in a machine of this type, by comparing predicted and measured blade loads, and by presenting predictions of blade loading in a future wind turbine.

DESCRIPTION OF WIND POWER SYSTEMS

Two ERDA-NASA wind power systems are discussed in this paper: (1) the 100 kW Mod-0 system, an experimental machine in operation at NASA's Plum Brook Station near Sandusky, Ohio, and (2) the 200 kW

Mod-0A system, now being assembled for installation as part of the municipal power plant of Clayton, New Mexico. The two wind turbines are almost identical in outward appearance. Both have two-bladed downwind rotors 125 feet in diameter and are mounted on truss towers with shaft elevations of 100 feet.

Figure 1 is a general view of the Mod-0 wind turbine. The design, fabrication, installation, and initial testing of this machine are described in references 1 to 10. The Mod-0 wind power system develops its rated power of 100 kW at a wind speed of 18 mph, while the Mod-0A system is designed to produce 200 kW of power at a wind speed of 24 mph. Both machines have rotor speeds of 40 rpm.

There are several structural differences between the Mod-0 and Mod-0A wind turbines. Mod-0A blades are stronger and somewhat heavier than Mod-0 blades (2300 lb versus 2000 lb). The Mod-0A tower is an all-pipe truss while only the legs of the Mod-0 tower are pipes. The Mod-0A gear box, high speed shaft and generator are all larger than the same equipment in the Mod-0 power system.

EARLY MOD-0 OPERATING EXPERIENCE

The Mod-0 wind turbine first achieved its rated speed and power in December of 1975. While its performance was generally as predicted, bending loads measured near the blade roots were very high. At wind speeds of 35 mph, bending moments were measured which were two to three times as large as expected. This was true for both flatwise (out-of-plane) and edgewise (in-plane) moment loads. Continued operation at these high levels of load would have resulted in early fatigue failure of the blades. An intensive study of the data recorded during this brief period of operation in December, 1975, was undertaken to (1) determine the causes of these excessive blade loads and (2) recommend modifications to reduce loads.

RESULTS OF VIBRATORY LOADS STUDY

Flatwise Blade Loading

The dynamic loading of the Mod-0 blade in the flatwise direction is dominated by the impluse applied to the blade each time it passes through the tower's wake. It was concluded that the Mod-0 tower was blocking the airflow to a much greater degree than expected and that this was the cause of the excessive flatwise blade loads. It was recommended that the service stairs and elevator rails originally installed in the tower be removed. These items are shown in figure 2.

Wind tunnel tests of scale models of the tower with and without stairs confirmed that the blockage was very high with stairs and was greatly reduced when they were removed (ref. 11).

Figure 3 shows the general testing procedure and some of the results of the wind tunnel tests. As shown in figure 3(a) the average velocity reduction $\Delta\overline{V}$ over the width of the tower w_t was determined for various tower orientations and elevations. Tower blockage was then calculated as the ratio of this average velocity reduction to the free stream velocity V_o. Figure 3(b) summarizes the data obtained. Using the 90 percentile numbers shown, removing the stairs reduced the blockage from 0.64 to 0.35. As a result flatwise blade loads would be reduced by about one-third. To further reduce blockage, the Mod-0A tower will be fabricated using structural pipes for all truss elements. As shown in figure 3(b) the use of round sections throughout the truss produces a small but significant additional reduction in tower blockage.

Edgewise Blade Loads

Examination of the harmonic content of the excessive edgewise blade loads led to the conclusion that these loads were caused by nacelle yawing motion. Figure 4 is a general view of the nacelle and its equipment. As originally constructed, the nacelle was connected torsionally to the tower by means of a single yaw drive shaft. It was determined that the

spring constant of this shaft in torsion produced a yawing resonance which resulted in large lateral motions of the rotor hub. These motions in turn were assumed to cause edgewise blade loads in a manner analogous to that known for airplane propellers (ref. 12).

To reduce edgewise loads it was recommended that the single yaw drive be replaced by the dual drive system shown schematically in figure 5. Nacelle motions would then be reduced, because of three factors: (1) avoidance of a resonance, whic·· was of greatest significance, (2) stiffening the nacelle-to-tower connection, and (3) eliminating the free play and non-linearity present in the single yaw drive system. The latter two items are illustrated by figure 6.

In figure 6, yaw moment is plotted versus yaw rotation of the nacelle for both the single and dual yaw drives, the latter with varying amounts of pre-torque. A pre-torque of about 50, 000 lb-in was recommended for the dual yaw system. In this way the rotation caused by a nominal yaw moment of 80, 000 lb-ft would be reduced by 60 percent, from 0. 42 deg to 0. 16 deg.

EFFECTS OF THE MOD-0 STRUCTURAL MODIFICATIONS

Removal of the service stairs and elevator rails and installation of the dual yaw drive were completed in April, 1977. Preliminary blade loading data which show the effects of the modifications are shown in figures 7 and 8.

Flatwise Moment Loads

In figure 7, cyclic flatwise moments at station 40 in the blade shank (40 in. from the rotor axis) are plotted versus nominal wind speed. Cyclic moment is equal to one-half the difference between the maximum and minimum values of moment during one revolution of the rotor. Data are represented by mean values together with an estimated varia-

tion of $\pm 1\sigma$ ($\pm$34 percent of the data about the mean). Variations are caused by changes in wind direction and velocity, control changes, and unsteady factors not yet identified.

The crossed symbols represent data obtained during December, 1975, during initial operation of the wind turbine. The open symbols are data taken after the structural modifications were made. Reductions in load are substantial, varying between one-third and one-half. In addition, the predicted load levels as a result of structural modification are verified by these preliminary data.

The circular symbols represent operation with the generator connected to a resistance load bank. The square symbols are data for operation synchronized with a utility network.

Edgewise Moment Loads

Figure 8 presents edgewise cyclic bending moment data before and after structural modifications. The modifications have decreased both the mean loads and their variation dramatically. This is particularly evident when the gravity cyclic load is recognized as the minimum possible value. Predictions of edgewise load were found to be somewhat conservative.

MOD-0A BLADE LOADS

The load calculation methods verified by the data in figures 7 and 8 were used to predict blade loads for the Mod-0A wind turbine. These predicted loads are shown in figures 9 and 10. As shown in figure 9, the strengthened Mod-0A blade should be free of fatigue damage from flatwise loads over almost all of its operating range. The same is true for edgewise cyclic loads, according to the predictions shown in figure 10.

CONCLUSIONS

1. The sources of excessive blade loads in the Mod-0 wind turbine as originally constructed were correctly identified.

2. The recommended structural modifications were successful in reducing blade loads to acceptable levels.

3. Methods for predicting blade loads were verified by recent data obtained on the modified Mod-0 wind turbine.

4. The Mod- 0A blades should be free of fatigue damage over almost all the normal operating range of wind speeds.

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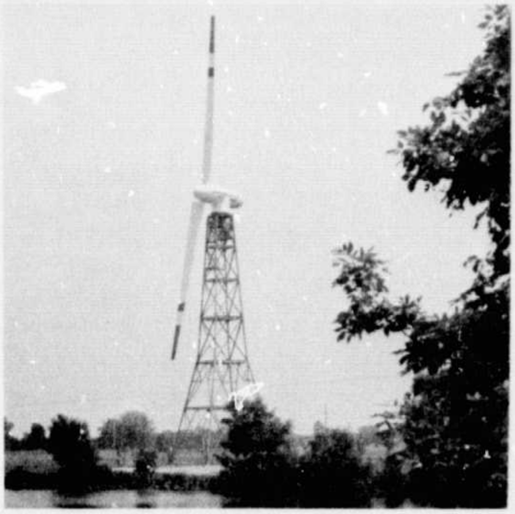


Figure 1. - ERDA/NASA 100 Kw Mod-O wind turbine, located at NASA's Plum Brook Station near Sandusky, Ohio (rated wind speed, 18 mph; rotor speed, 40 rpm; rotor diameter, 125 ft; rotor axis elevation, 100 ft).

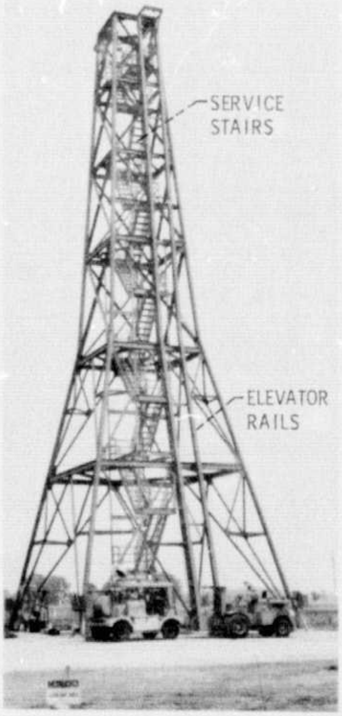
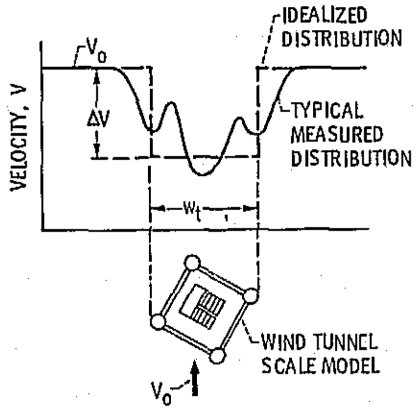
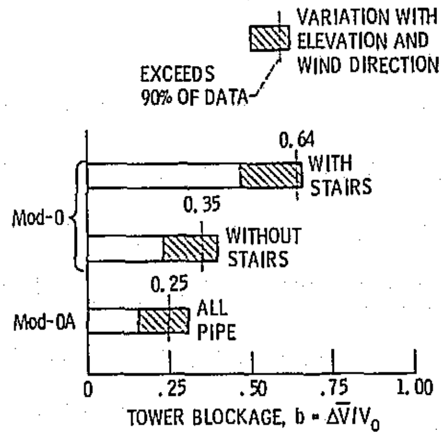


Figure 2. - Original Mod-O tower, with service stairs and elevator rails which have since been removed.



(a) DIAGRAM SHOWING TEST SETUP AND TYPICAL DATA TAKEN.



(b) SUMMARY OF RESULTS OF Mod-0 AND Mod-0A TOWER MODEL TESTS.

Figure 3. - Wind tunnel tests of tower models (1/24th scale) to determine amount of wind blockage.

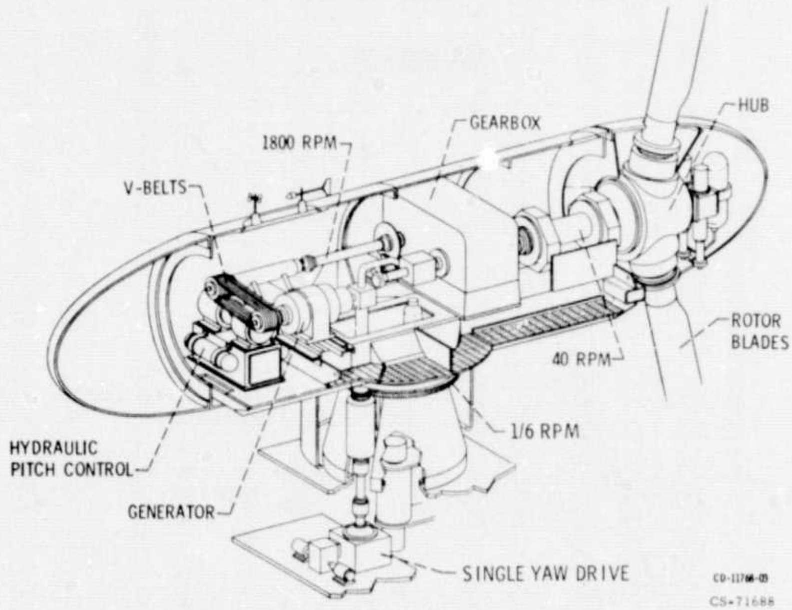


Figure 4. - Schematic view of Mod-O wind turbine nacelle and equipment, showing original single yaw drive system.

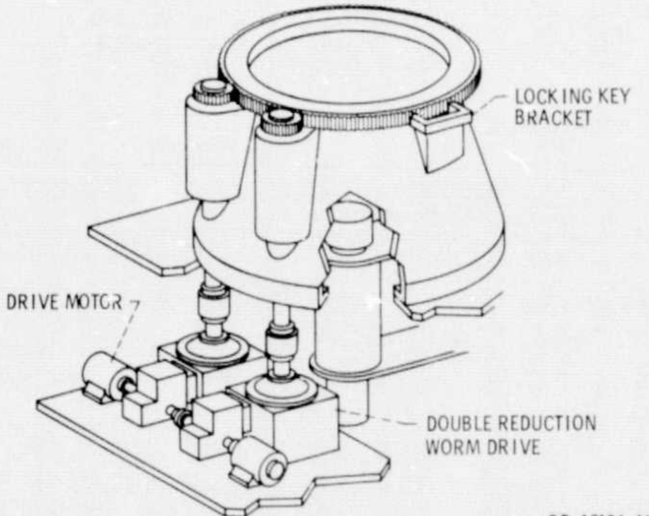


Figure 5. - Schematic view of dual yaw drive system which replaces single system.

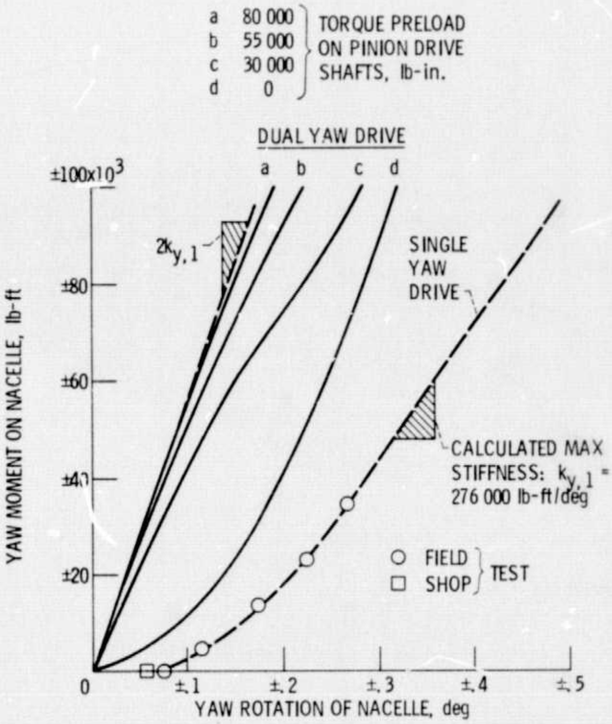


Figure 6. - Nacelle yaw moment versus yaw rotation for single and dual yaw drive systems.

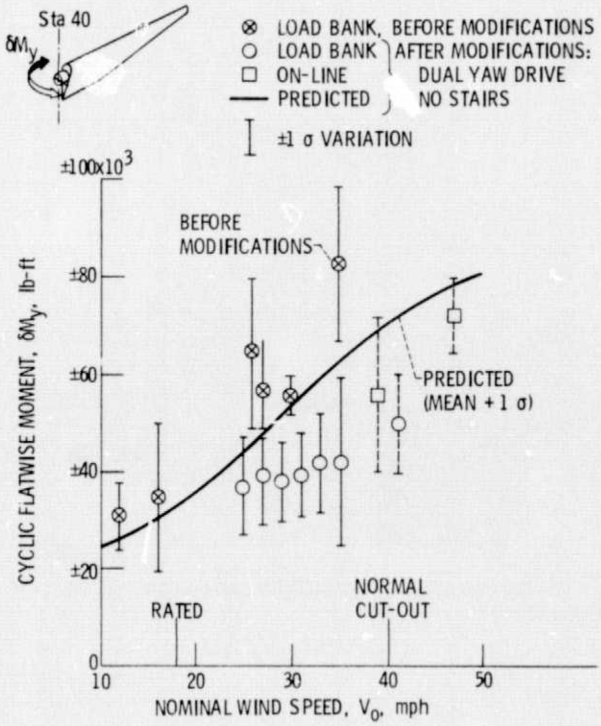


Figure 7. - Cyclic flatwise bending loads in Mod-0 blades before and after structural modifications.

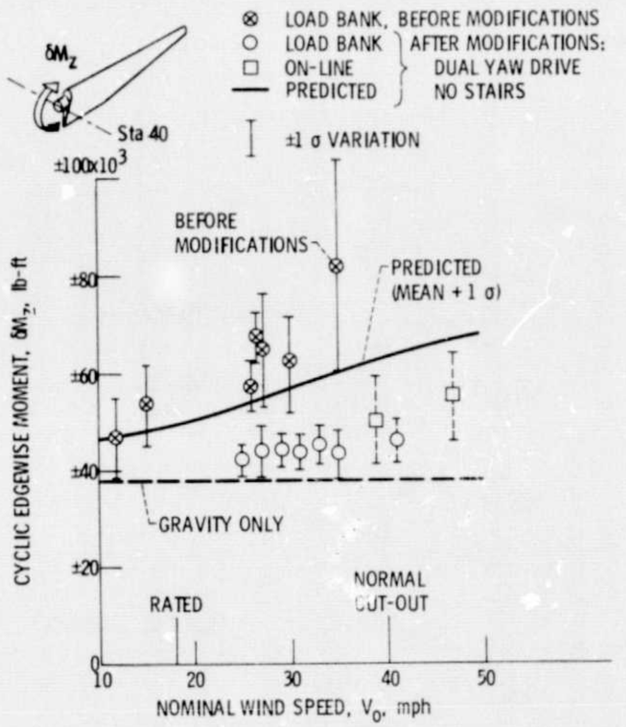


Figure 8. - Cyclic edgewise bending loads in Mod-0 blades before and after structural modifications.

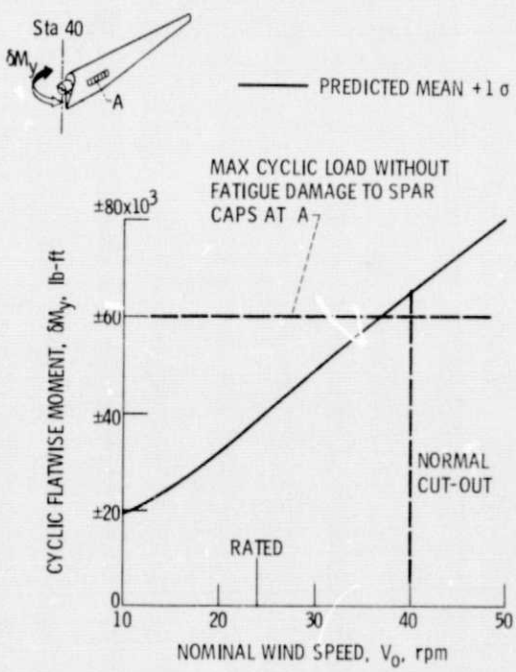


Figure 9. - Predicted cyclic flatwise bending loads for Mod-0A blades.

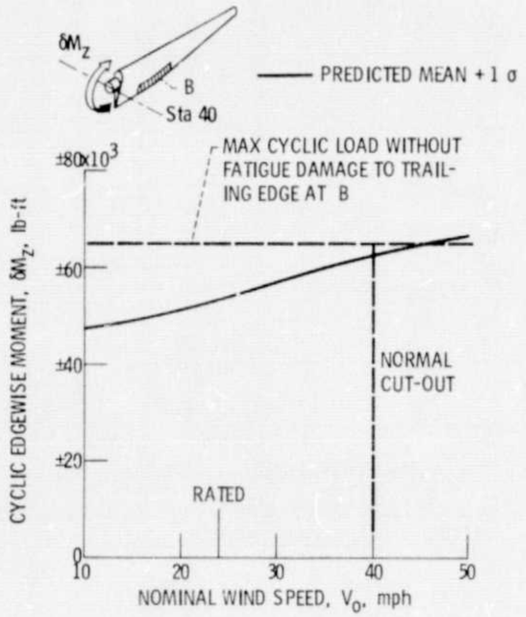


Figure 10. - Predicted cyclic edgewise bending loads for Mod-0A metal blades.